VECTOR SPACES

IDEA: Abstract our understanding of linear systems...
↳ Build a language to prove more powerful theorems.

Def^n: A (real) vector space is a set V (whose elements are vectors) with operations

(hidden) Closure axioms

$$+ : \underline{V} \times \underline{V} \longrightarrow \underline{V} \qquad \text{(vector addition)}$$

$$\cdot : \mathbb{R} \times \underline{V} \longrightarrow \underline{V} \qquad \text{(scalar multiplication)}$$

satisfying the following axioms:

① $u + v = v + u$ for all $u, v \in V$ (Commutativity of Addition)

② $u + (v + w) = (u + v) + w$ for all $u, v, w \in V$ (Associativity of Addition)

③ There is a vector $0 \in V$ such that for all $v \in V$ $0 + v = v$. (Zero vector) NB: 0 is the zero-vector

④ For all $v \in V$ there is a vector $w \in V$ such that $v + w = 0$. (Additive inverses) NB: usually we denote $w = -v$.

⑤ $a \cdot (u + v) = (a \cdot u) + (a \cdot v)$ for all $a \in \mathbb{R}$ and all $u, v \in V$. (Scalar distribution over vector addition)

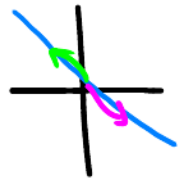
⑥ $(a + b) \cdot v = (a \cdot v) + (b \cdot v)$ for all $a, b \in \mathbb{R}$ and all $v \in V$. (Vector distribution over scalar addition)

⑦ $a \cdot (b \cdot v) = (ab) \cdot v$ for all $a, b \in \mathbb{R}$ and all $v \in V$ (Associativity of Scalar multiplication)

⑧ $1 \cdot v = v$ for all $v \in V$. (Scalar Identity).

Ex: $\mathbb{R}^n$ is a vector space for all n.
(we verified this awhile back).

Ex: Let $V = \{(x,y) \in \mathbb{R}^2 : x = -y\}$. With operations



$$(x_1, y_1) + (x_2, y_2) = (x_1 + x_2, y_1 + y_2)$$
and $$c \cdot (x,y) = (cx, cy),$$
this set V is a vector space.

pf: First we need to show for $u, v \in V$ and $c \in \mathbb{R}$ we have $u + v \in V$ and $c \cdot v \in V$.
(i.e. closure of V under addition and scalar mult).

Let $u, v \in V$ and $c \in \mathbb{R}$. So $u = (u_1, u_2)$ and $v = (v_1, v_2)$ satisfy $u_1 = -u_2$ and $v_1 = -v_2$.

Now $u + v = (u_1, u_2) + (v_1, v_2) = (u_1 + v_1, u_2 + v_2)$ and we know $u_1 + v_1 = (-u_2) + (-v_2) = -(u_2 + v_2)$, so $u + v \in V$. On the other hand,

$cu = c(u_1, u_2) = (cu_1, cu_2)$ and because $u_1 = -u_2$, we have $cu_1 = c(-u_2) = -(cu_2)$, and hence $cu \in V$. Hence V is closed under vector addition and scalar multiplication.

Next we verify the 8 (remaining) conditions on a vector space:

Let $u = (u_1, u_2)$, $v = (v_1, v_2)$, $w = (w_1, w_2) \in V$ and $a, b \in \mathbb{R}$:

① (Commutativity):

$$u + v = (u_1, u_2) + (v_1, v_2) = (u_1 + v_1, u_2 + v_2)$$

$$= (v_1 + u_1, v_2 + u_2) = (v_1, v_2) + (u_1, u_2) = v + u \checkmark$$

② (Associativity of Vec. add.)

$$u + (v + w) = (u_1, u_2) + ((v_1, v_2) + (w_1, w_2))$$

$$= (u_1, u_2) + (v_1 + w_1, v_2 + w_2)$$

$$= (u_1 + (v_1 + w_1), u_2 + (v_2 + w_2))$$

$$= ((u_1 + v_1) + w_1, (u_2 + v_2) + w_2)$$

$$= (u_1 + v_1, u_2 + v_2) + (w_1, w_2)$$

$$= ((u_1, u_2) + (v_1, v_2)) + (w_1, w_2)$$

$$= (u + v) + w$$

③ We claim $0_V = (0,0)$ is the zero-vector for V.
Indeed, $0_V + v = (0,0) + (v_1, v_2) = (0 + v_1, 0 + v_2) = (v_1, v_2) = v$.
Moreover, $0 = -0$, so $(0,0) \in V$.

④ (Additive Inverses). For vector v, we have

$$v + (-v_1, -v_2) = (v_1, v_2) + (-v_1, -v_2) = (v_1 - v_1, v_2 - v_2) = (0,0)$$

on the other hand $(-v_1, -v_2) = -1 \cdot (v_1, v_2) = -1 \cdot v \in V$.

⑤ (distribution I).

$$a \cdot (u + v) = a \cdot (u_1 + v_1, u_2 + v_2) = (a(u_1 + v_1), a(u_2 + v_2))$$

$$= (au_1 + av_1, au_2 + av_2) = (au_1, au_2) + (av_1, av_2)$$

$$= (a \cdot u) + (a \cdot v)$$

⑥ (distribution 2).

$$(a+b)\cdot v = ((a+b)v_1, (a+b)v_2)$$
$$= (av_1 + bv_1, av_2 + bv_2)$$
$$= (av_1, av_2) + (bv_1, bv_2)$$
$$= (a\cdot v) + (b\cdot v)$$

⑦ (Scalar association)

$$a\cdot(b\cdot v) = a\cdot(bv_1, bv_2) = (a(bv_1), a(bv_2))$$
$$= ((ab)v_1, (ab)v_2) = (ab)\cdot v$$

⑧ (Scalar Unit)

$$1\cdot v = 1\cdot(v_1, v_2) = (1v_1, 1v_2) = (v_1, v_2) = v$$

Hence V is a vector space under these operations! $\boxed{//}$

Remark: These checks are mostly just the same work we did showing properties of vect. add. earlier...

Ex: Let $P_n(\mathbb{R})$ denote the set of polynomial's with real coefficients and degree at most n.
Let $+ : P_n(\mathbb{R}) \times P_n(\mathbb{R}) \to P_n(\mathbb{R})$ be the usual polynomial addition, and scalar multiplication $\cdot : \mathbb{R} \times P_n(\mathbb{R}) \to P_n(\mathbb{R})$ be the usual multiplication.

Then $P_n(\mathbb{R})$ is a vector space.

Special Case: When $n=3$, we have

$$P_3(\mathbb{R}) = \{ p(x) : p(x) \text{ has degree at most } 3 \}$$
$$= \{ a_0 + a_1 x + a_2 x^2 + a_3 x^3 : a_0, a_1, a_2, a_3 \in \mathbb{R} \}$$

And the addition acts like so:

$$(a_0 + a_1 x + a_2 x^2 + a_3 x^3) + (b_0 + b_1 x + b_2 x^2 + b_3 x^3)$$
$$= (a_0 + b_0) + (a_1 + b_1) x + (a_2 + b_2) x^2 + (a_3 + b_3) x^3$$

and scalar multiplication works like that:

$$c(a_0 + a_1 x + a_2 x^2 + a_3 x^3) = (c a_0) + (c a_1) x + (c a_2) x^2 + (c a_3) x^3$$

↳ Check the conditions are satisfied! $\boxed{//}$

Ex: Let $m, n \geq 1$. The set

$$M_{m,n}(\mathbb{R}) = \{ A : A \text{ is an } m \times n \text{ matrix w/ real entries} \}$$

is a vector space under matrix addition and entry-wise scalar multiplication. $\boxed{//}$

Ex: Let $V = \{ f : f \text{ is a function } \mathbb{N}_0 \to \mathbb{R} \}$.

Define $(f+g)(x) = f(x) + g(x)$ and $(cf)(x) = c f(x)$

Then V is a vector space under these operations.

↳ Very GOOD exercise to verify this...

Prop: Let V be a vector space.

⓪ $0 \cdot v = 0_V$ for all $v \in V$.

① $-1 \cdot v$ is the additive inverse of v for all $v \in V$.

② $c \cdot 0_V = 0_V$

pf: Let V be a vector space and let $v \in V$ be arbitrary.

⓪ $0 \cdot v = (0+0) \cdot v = (0 \cdot v) + (0 \cdot v)$

Hence, letting w denote the additive inverse of $0 \cdot v$

we have $(0 \cdot v) + ((0 \cdot v) + w) = 0 \cdot v + 0_V = 0 \cdot v$

while $((0 \cdot v) + (0 \cdot v)) + w = 0 \cdot v + w = 0_V$

Hence we have $0 \cdot v = 0_V$ as desired.

Rest of proof is next time... $\boxtimes$